Invited Paper

Measurement and Control Technology in Analog IC Design

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Section 1: Introduction

Analog technology is very important in commercial and industrial instruments and systems – such as measuring instruments and automatic control systems -- that have analog inputs and outputs. Consumer equipment drives demand for improvements in analog circuit performance, and this naturally leads to performance improvements in commercial and industrial equipment.

Fig.1 shows a representative piece of high-end measuring equipment: a new digital oscilloscope with 40Gsps ADC. This ADC is fabricated using an ordinary CMOS process which is mainly used for consumer applications. This example shows clearly that improvements in methods of fabricating analog circuits for consumer use can lead to improvements in measurement instruments. However, it is also true that it is impossible to achieve such high performance just by using the latest CMOS process. The power consumption of the ADC is much higher than usual consumer devices, so it requires special cooling techniques.

Fig.1 Outlook of Agilent DSO80000B series digital oscilloscope.

The converse also applies: even in LSIs used for ordinary consumer equipment, like audio-visual equipment and cellular phones, we often find techniques that originated in measuring instruments and automatic control systems. In this paper, we would like to argue that measuring and automatic control technologies can provide valuable tools in designing high-performance analog and mixed-signal integrated circuits:

Section 2: Calibration - Basic Theory and Background

"Calibration" is an important part of measurement technology. In measurement applications, we understand "calibration" to mean "to guarantee the performance" and "to maintain traceability to national standards". Nowadays we sometimes find the term "calibration" used to mean "self-tuning", or "error correction" in analog LSI design for consumer equipment.

Fig.2 shows the block diagram of a simple measurement system with offset-compensation functions. This system measures and displays the input voltage. When offset-voltage-compensating calibration is started, the input of this system is connected to 0V and the value of the offset voltage is stored in a memory device. Then, in measurement mode, we subtract the stored offset value from the raw data to obtain the offset-compensated result. By such automatic offset-compensation, we can eliminate offset voltage error.

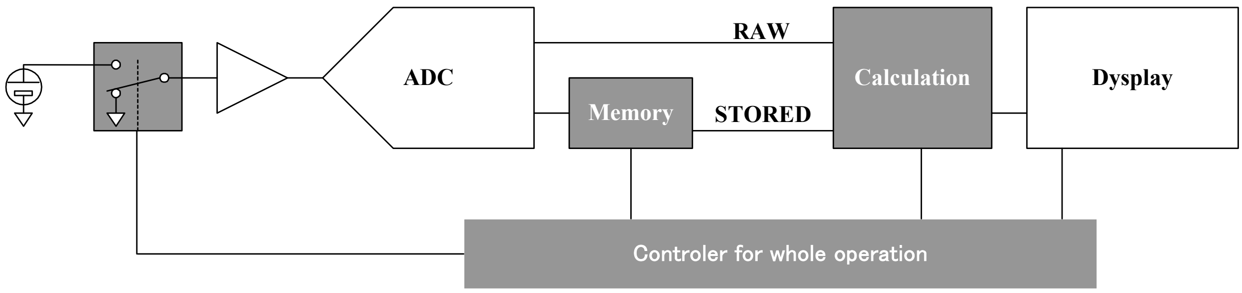


Fig.2: Block diagram of a simple measurement system with calibration function.

In addition to the essential measuring functions, this compensation method requires additional elements: a connection circuit which switches the input between the input to be measured (from outside the system) and a known calibration voltage, memory devices for storing the measured offset value for offset compensation, calculation functions, and a controller to sequence the whole operation. In the past, adding such elements increased the cost, which was difficult to justify for cost-sensitive applications like consumer equipment.

However nowadays, thanks to the rapid progress in CMOS technology, this situation is changing. The cost of building such elements with CMOS digital circuits, the cost of memory, calculation circuits and controller can be quite small. Furthermore, because SoC (System on a Chip) devices for consumer application include embedded MCUs (Micro Control Units) such as ARM processors, it is possible to realize calibration functions simply by developing software. Hence, even for cost sensitive consumer devices, it is becoming practical to use calibration to improve analog performance and reliability.

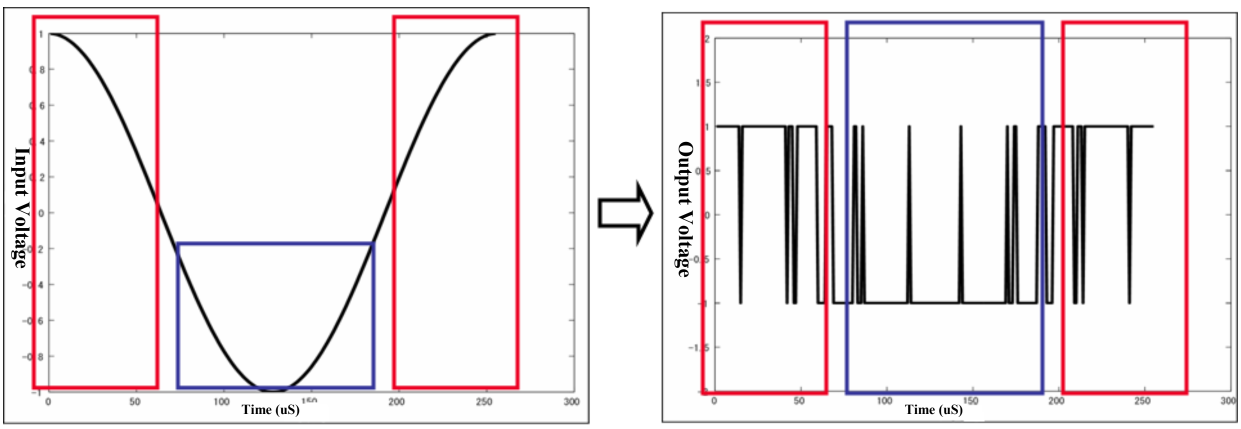
Section3: Repeatability and Reference

The cost of digital circuitry is not the only consideration when trying to improve analog performance by adding calibration functions to consumer ICs. In Fig.2, if the offset voltage of this system changes from the value stored at calibration time, the offset error is not cancelled. Hence offset voltage itself is not a problem, but the stability – the "repeatability" -- of the value is important.

In usual analog IC design, the main cause of repeatability degradation is temperature fluctuation. So in classical methods of designing analog ICs with calibration, we need to take much care in minimizing thermal drift. However in modern designs, we can repeat calibration very frequently. For example, if we repeat calibration at one-second intervals, it is possible to cancel thermal drift caused by slow changes in room temperature. Furthermore, nowadays it is also possible to repeat calibration at intervals as small as one millisecond or less.

Next we would like to mention the importance of the reference signal. Even if we perform frequent calibration to cancel thermal drift, the calibration will be meaningless if the reference voltage used for calibration varies with temperature. In other words, the stability of the reference voltage cannot be improved by calibration, and therefore we have to prepare a stable reference. Here I would like to emphasize that it is much easier to prepare a stable reference than to keep the whole system stable against temperature fluctuation. In practical circuits, inexpensive voltage reference devices, such as band-gap (or Zener) references, are widely used for this purpose.

Because of rapid progress in CMOS digital systems, it has becomes possible to perform complex arithmetic calculations for sophisticated calibration within LSIs. But for the calibration to be meaningful, it is important to prepare a proper reference. For example, to cancel the non-linearity of an analog circuit, such as an ADC, we need to prepare a stable variable-voltage reference with sufficient linearity. And from the viewpoint of IC design, this proper reference has to be realized inexpensively, within an LSI circuit.



PWM Input Signal PWM Output Signal

Fig.3 Explanation of PWM signal.

One way to solve this problem is to use PWM (Pulse Width Modulation) with a stable clock. By using PWM, we can generate a voltage proportional to the number of pulses with a uniform period. Since it is based on "counting", it can be realized using digital circuitry, and also the PWM signal is linear enough for most applications. Fig.3 shows the basic operation of PWM.

By using such techniques, we can perform effective and complex linearity compensation even in LSIs.

Section 4: Control Theory Applied to Analog IC Design

Automatic control technology is another important field in industrial equipment.

Control theory was initially developed for systems like chemical and steel plants. But, nowadays, control theory cannot be ignored in analog IC design.

Here we would like to introduce an example which shows the effectiveness of applying control theory to analog circuit design. Track and Hold (T/H) circuits are a key component of many ADCs (Fig.4). They hold the input voltage while one AD conversion is being performed (hold mode). As soon as the conversion completes, T/H again follows the input signal (track mode). The total conversion time of the ADC is decided by the sum of the hold period and the track period. The hold period depends on the method of AD conversion, and the track period depends on the speed of T/H circuit; therefore optimization of the T/H circuit is important to maximize the conversion rate of the ADC.

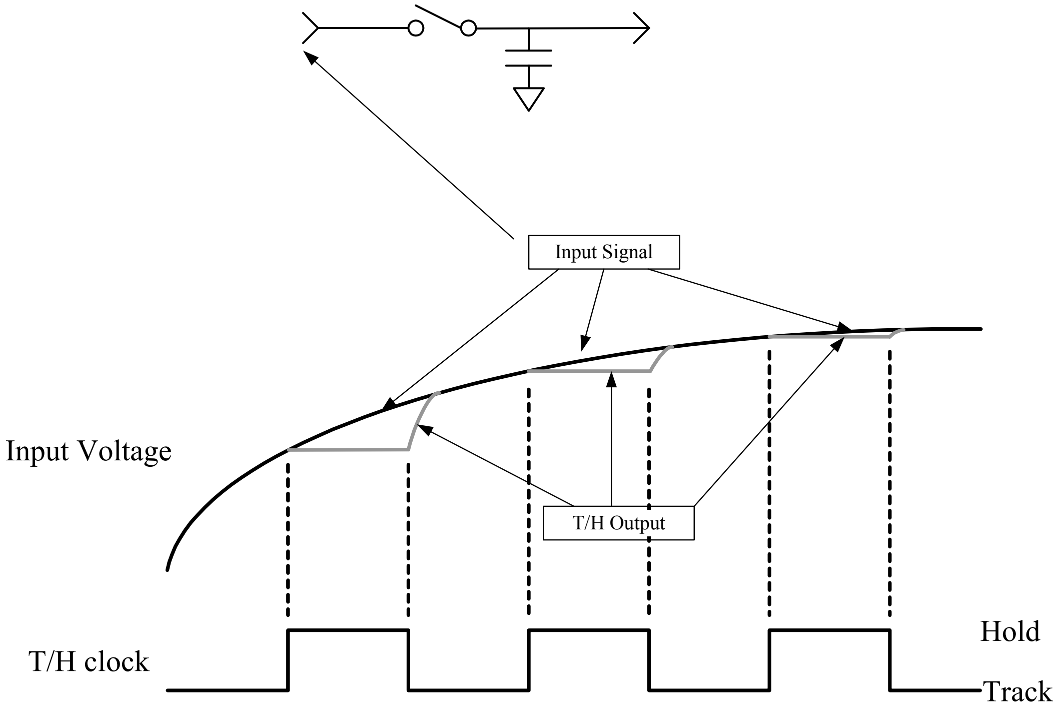
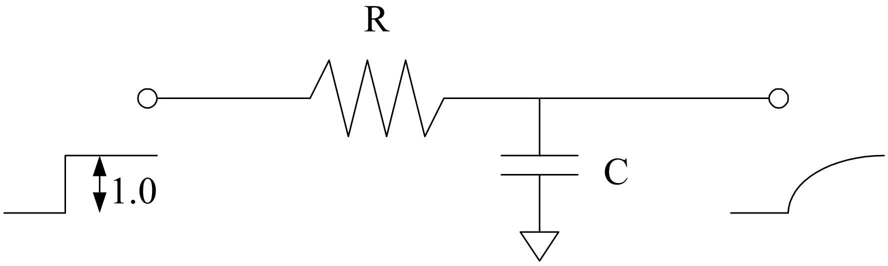
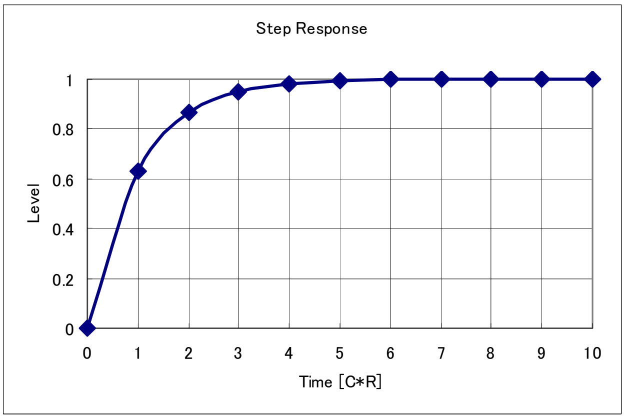


Fig.4: Operation of a track and hold circuit.

Fig.5 shows a simplified model of a T/H circuit. In hold mode, the switch in the figure is kept open, so electric charge stored in the capacitor cannot leak, and the voltage across the capacitor is kept at a fixed value. In track mode, the switch is closed, so the capacitor is charged up to the same voltage as the input. But the switch in the T/H circuit is usually made using CMOS transistors, so a real-world switch has some resistance. (R). Hence, the optimization of T/H circuits is recognizable as a single-pole step-response problem in control theory.

In the practical design of T/H circuits, other parasitic elements exist, so the optimization problem becomes more complex. It is not good to depend only on sixth sense in solving such complex problems -- control theory is of more help in reaching an optimal solution.





$$f(t) = 1 - e^{-\frac{t}{c*R}}$$

$$t = 6.91c*R$$
$$f(t) = 0.99999$$

Fig.5: Simplified model of the track and hold circuit.

The second example is the design of switching DC-DC converters (Buck-Boost converters) with PWM or PFM (Delta-Sigma modulation) control signals [1]. Precise control requires accurate control voltage signals with small ripple. A controller with fast response maintains good voltage regulation (with small overshoot/undershoot) for an output current step. In power systems, location of the power supplies to reduce stray inductance in layout patterns is very important, because inductance delays the response and degrades the regulation.

Section 5: Other Examples of Industrial Techniques Applicable to Analog IC design

Here are some other examples of measurement and control techniques applicable to analog integrated circuit design. Some of them will be suitable topics for discussion at the conference:

Here are some other examples of measurement and control techniques applicable to analog integrated circuit design. Some of them will be suitable topics for discussion at the conference:

- Self-calibration techniques in ADC/DAC and also RF circuits and systems.
- Digital error correction techniques with redundant hardware in ADC/DAC [2].
- Accurate and robust bias voltage regulators that are not affected by variation in process, supply voltage, or temperature.

● Automatic tuning of cut-off frequency and Q-value in continuous-time analog filters.
● On-chip monitoring circuitry (measuring power supply voltage fluctuation, timing jitter etc.)
● Control systems for power supplies (DC-DC converters) with fast response and low ripple.
● Automatic gain control circuits.
● Design and analysis methodology, such as Laplace transforms, Fourier transforms, Bode charts, Nyquist stability criteria, Routh-Hurwitz stability criteria, transfer functions, impulse response, step response (linear system theory, feedback theory)
● Operational amplifier design (especially stability problems, phase margin, gain margin)
● Spread-spectrum clocking of digital circuitry and switching regulators for EMI reduction [3].
● Sampling techniques (oversampling, equivalent-time sampling, sequential sampling, random sampling, subsampling, down-sampling, up-sampling, impulse sampling, sampling rate conversion) [4].
● Built-in-self-test (BIST) and built-out-self-test (BOST), especially for analog circuit testing [5].
● Stability studies for higher-order delta-sigma modulators.

Section 6: Possible Collaboration with Others

We would like to collaborate with researchers in measurement and control fields who are interested in analog technologies; our target is development of high performance analog ICs.

Section 7: Conclusion

In conclusion, we have found that measurement and automatic control technologies that were originally developed for commercial and industrial use can provide effective tools for high-performance next-generation analog IC design.

We would like thank K. Wilkinson for valuable discussions.

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Biography of Dr. Takanori KOMURO:

Takanori Komuro received the B.E. degree in electric engineering from University of Tokyo in 1985. Then he joined Yokogawa Electric Corp. Tokyo, Japan, where he was engaged in the research and development of AD converters for measurement instruments. From 1991 to 1995, he was involved in the research project, Superconducting Sensor Laboratory, about development of brain activity sensing system (MEG). In 1995, he was invited as researcher by Kanazawa Institute of Technology, where he worked for making MEG system fit for practical use. From 1997, he joined Hewlett-Packard Japan, Ltd., (Currently company name has changed into Agilent Technologies International, Japan, Ltd.), where he involved in development of analog portion, from DC to several GHz, for LSI tester. And he also has researched about test methods for various kind of LSIs. He received Ph.D. degree from Gunma University in 2007.

Biography of Prof. Haruo KOBAYASHI:

Haruo Kobayashi received the B.S. and M.S. degrees in information physics from University of Tokyo in 1980 and 1982 respectively, the M.S. degree in electrical engineering from University of California at Los Angeles（UCLA） in 1989, and the Dr. Eng. degree in electrical engineering from Waseda University in 1995. He joined Yokogawa Electric Corp. Tokyo, Japan in 1982, where he was engaged in the research and development related to measuring instruments and mini-supercomputers. From 1994 to 1997, he was involved in research and development of ultra-high-speed ADCs/DACs at Teratec Corp. In 1997 he joined Gunma University and presently is a Professor in Electronic Engineering Department there. He was also an adjunct lecturer at Waseda University from 1994 to 1997. His research interests include analog & digital integrated circuits design and signal processing algorithms. He received Yokoyama Award in Science and Technology in 2003, and the Best Paper Award from the Japanese Neural Network Society in 1994.

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